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THE CONTRIBUTION FROM SCATTERED LIGHT TO QUASAR GALAXY HOSTS

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ABSTRACT

We present models representing the scattering of quasar radiation off free electrons and dust grains in geometries that approximate the structure of quasar host galaxies. We show that, for reasonable assumptions, scattering alone can easily produce ratios of nuclear (point source) to extended fluxes comparable to those determined in studies of quasar hosts. This result suggests that scattered quasar light, as well as stellar emission from the host galaxy, contributes significantly to the detected extended flux, leading to uncertainty in the inferred properties of quasar host. A significant contribution from scattered quasar light will lead to overestimates of the luminosity and hence mass of the host galaxy, and may also distort its morphology. Scattering of quasar light within the host galaxy may provide alternative explanations for the apparent peak in host luminosity at $z = 2-3$; possibly the overall average higher luminosity of radio-loud host galaxies relative to those of radio-quiet quasars (RQQs), and the apparent preference of high-luminosity RQQs for spheroidal rather than disk galaxies.

Key words: galaxies: active – galaxies: fundamental parameters – galaxies: general – polarization – scattering

1. INTRODUCTION

There have been numerous ground-based (e.g., Aretxaga et al. 1998; Falomo et al. 2008) and space-based (e.g., Kukula et al. 2001; McLure et al. 2004) studies to characterize the host galaxies of quasars at $z \gtrsim 0.4$. These studies suggest that the host galaxies of radio-loud quasars (RLQs) at high redshift are $\sim 2.5-3$ mag brighter than at the present epoch and have evolved in a manner that is consistent with a formation epoch at $z \sim 3$ and subsequent simple passive stellar evolution. A similar evolutionary trend has been suggested for radio-quiet quasar (RQQ) hosts with the addition of a small increase in active galactic nucleus (AGN) fueling efficiency with increasing redshift (Kukula et al. 2001). However, other authors (e.g., Falomo et al. 2008; Schramm et al. 2008, and references therein) found evidence that high-redshift hosts are brighter than can be explained by passive evolution or that the ratio of black-hole mass to spheroid mass is greater than that determined for the local universe (e.g., McLure et al. 2006; Peng et al. 2006). The inconsistencies in the calculated relative strength of the presumed host galaxy raises questions as to the overall validity of these detections. Also, it is generally found that powerful nuclear activity, typical of quasars, at $z \gtrsim 0.4$ is predominantly associated with bulge-dominated galaxies, regardless of radio luminosity (McLure et al. 1999, 2004; Dunlop et al. 2003; Falomo et al. 2008).

However, all these studies have neglected the potentially important contribution of scattered nuclear (quasar) light to the surrounding nebula. In a luminous quasar, it is possible that scattering off free electrons and dust within the host galaxy will compete with, or possibly entirely dominate, the direct emission from the host galaxy itself.

The signature of the presence of significant scattered nuclear light, as witnessed by its polarization properties, is widespread in AGNs. Indeed, polarimetric measurements have brought about some of the greatest leaps in our physical understanding of these objects. The most prominent example being the formulation of the unified scheme of AGNs (e.g., Antonucci 1993, and references therein). Subsequent studies have shown that many

radio galaxies are surrounded by spatially resolved reflection nebulae (e.g., PKS 2152-69, di Serego-Alighieri et al. 1988 and Cygnus A, Tadhunter et al. 1990), with the polarized region extending over several kpc (di Serego-Alighieri et al. 1989).

In Seyfert 2 galaxies (e.g., NGC 1068, Capetti et al. 1995; Mrk 463, Uomoto et al. 1993; Mrk 3, Kishimoto et al. 2002) essentially all the extended UV light is scattered. In NGC 1068, the degree of polarization is as high as 60% in parts of the resolved scattering region. For the nearby Seyfert 1 galaxy NGC 4151, it is possible to trace scattering both in the traditional scattering cone and also within the host galaxy coincident with the extended narrow line region (Draper et al. 1992; Robinson et al. 1994). Significant polarization due to scattering is observed to extend to a distance of greater than 1.4 kpc.

The greater majority of bright QSOs, approximately 99%, are only marginally polarized with a degree of polarization of less than 3% and generally at the 1% level (Stockman et al. 1984). However, polarization measurements by themselves carry little information on the level of scattering or where it occurs. If the scattering region is unresolved, geometrical cancellation, i.e., summing of the polarization vectors oriented at different angles, as in the case of the centro-symmetric pattern, produces a null polarization. The measured polarization level is only an indication of the irregularities in the scattering region and is therefore a *lower limit* to the scattered flux fraction. This is true whether or not there is dilution, from a stellar component for example. Thus, for a typical observed quasar polarization of 1%, scattering will contribute 1% of the total observed flux if the scattered light is intrinsically 100% polarized. If the AGN to host galaxy ratio is 100, then the scattered component is equal in strength to the host galaxy. In real situations, an intrinsic polarization of 100% is not possible, so in fact, the scattered flux contribution would have to exceed 1% in order to maintain the same level of polarization. If we were to take NGC 1068 as an example, with an integrated intrinsic polarization of 16% (e.g., Young et al. 1995), then the scattered flux would account for 6.25% of the total observed flux, i.e., over six times brighter than the host galaxy at an AGN to host galaxy ratio of 100. Studies of the host galaxies of type 2 quasars, in which the AGN is

Table 1
Parameters Used in the Modeling

Parameter	Values	Units
Inclination	0, 30, 60, 90	°
α ($n = n_o(r_o/r)^\alpha$)	0, 1, 2	...
n_o (electrons; $\alpha = 0$)	$1 \times 10^4 - 1 \times 10^7$	m^{-3}
n_o (dust; $\alpha = 0$)	$1 \times 10^{-10} - 1 \times 10^{-6}$	m^{-3}
Distance	0.3, 1, 2, 4	z
r_o	10	pc
r	Simple sphere	2.5–20 kpc
	Spheroid	x, y : 2.5–20 kpc
		z : 8.7–80
	Disk	x, y : 2.5–20 kpc
		z (height): 1–4

obscured in the direct view, indicates that scattered nuclear light can be comparable to, or even dominate, the extended emission (Zakamska et al. 2006).

In this Letter, we aim to determine whether scattering in the host galaxy is a potential concern to host parameterization in high-redshift observations. In Section 2, we introduce the scattering model and in Section 3, we present the results of our modeling. We discuss these results in comparison to the observations in Section 4.

2. THE SCATTERING MODEL

We take the scattering model of Young (2000) as a starting point. This model can incorporate any source and scattering geometry that can be described analytically. The model allows for scattering off free electrons and dust grains in the Rayleigh regime. For dust scattering, we assume a refractive index that matches that of silicates (Simmons 1982) and that the particle is a sphere with a diameter of $0.1 \mu\text{m}$.

The simplest geometry to model, that has relevance to the problem at hand, is that of a sphere of scattering particles, be they dust particles or free electrons. It should be pointed out that the models presented here do not include any starlight from the host galaxy. The aim is to show whether scattering alone can produce an extended illuminated region comparable to those detected about QSO nuclei. In terms of the geometry of the scattering region, we will limit this case study to spheroid and disk regions. The spheroid cases represent elliptical galaxies and the disk-like region will represent the later type spiral galaxies. In addition, a combination of both the spheroid and disk regions can represent the early-type spiral and S0 galaxies.

In excess of 5000 individual model runs were executed, the ranges in input parameters are listed in Table 1. To facilitate comparison with observations, it was then necessary to convolve the model output images with the point-spread function (PSF) of a specific instrument. We chose to simulate images from the ACS and NICMOS cameras onboard the *Hubble Space Telescope* (HST) and thus, the images were binned at the respective pixel scales of 0.025 (for $z = 0.4$ galaxies for comparison with the observations of Floyd et al. (2004)) and 0.043 arcsec (for higher z objects). Model PSFs were constructed using the TINYTIM software using filters that corresponded to the rest wavelength range of Kukula et al. (2001).

The spheroid scattering region is defined in terms of an inner and outer scattering radius in the three principal geometrical axes and the inclination of the system z -axis to the line of sight. This allows for a variety of spheroid shapes but by keeping the x - and y -radii equal the more specific cases of oblate and

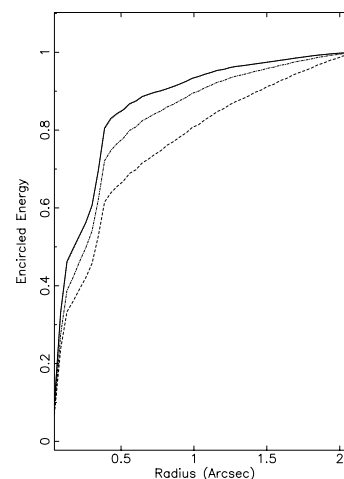


Figure 1. Azimuthally averaged radial profile for the NICMOS PSF (solid line) and three models representing scattering in a sphere of dust grains. The geometrical parameters of the sphere are described in the main text, but the exponent of the number density power law is 0 (dashed line), 1 (dot-dashed line), and 2 (dotted line) with the number density at the inner scattering radius set to give equal optical depth to scattering in each case. As plotted here, the profile for $\alpha = 2$ is indistinguishable from the PSF profile.

prolate spheroid regions can be studied. The number density of scattering particles is assumed to have a power-law distribution with radius, $n = n_o(r_o/r)^\alpha$, and the number density at the inner scattering radius, n_o , was chosen such that the scattering region remains optically thin.

The disk-like region is also defined in terms of an inner and outer radius in both the x - and y -axes with a variable vertical extent in the z -axis. Thus, the resultant geometry is that of a circular slab.

3. APPLICATION TO RADIAL PROFILES

The resultant radial profiles, for a simple spherical scattering region, are presented in Figure 1 for a redshift of $z = 2$ and convolved with the NICMOS PSF. Here, the radial profiles are formed by calculating the cumulative flux in a circular aperture of increasing radius and then normalized to the flux in the largest aperture. For the models presented in Figure 1, the scattering elements are dust particles and the optical depth to scattering is 0.5. For the case with $\alpha = 0$, the uniform number density is $3 \times 10^{-8} \text{ m}^{-3}$. It is readily apparent, even with this simplistic arrangement, that there is significant extended flux, at least for the cases with α equal to 0 and 1. Indeed, with $\alpha = 0$ there is ~ 2 times more flux at a radial distance of 0.5 arcsec than for the point-source PSF alone.

The relatively low observed polarization of most quasars (Section 1) is an important constraint on the scattering models. The simple sphere of scattering particles produces a true centrosymmetric pattern of polarization vectors and on integration, for all values of aperture radius, the degree of polarization is zero. A disk-like scattering region, with high optical depth to scattering (uniform electron number density of 10^7 m^{-3} —equatorial optical depth to scattering = 0.5) at an inclination of 90° gives an integrated degree of polarization of 1.3% when the disk is thin (an aspect ratio of 0.05), dropping to 0.8% as the disk thickness increases (an aspect ratio of 0.2).

The ratio of the quasar flux to that of the “host galaxy” is an important parameter in the studies of high-redshift AGNs. The simple sphere model in Figure 1, with $\alpha = 0$, results in a quasar to extended-flux ratio of 1.3. Reducing the dust

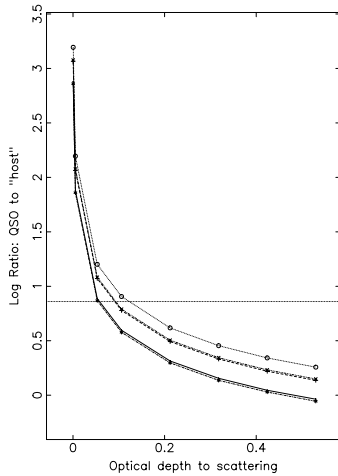


Figure 2. The ratio of the quasar flux to that of the extended flux for varying optical depth to scattering. Models for several scattering geometries are plotted: spherical (solid line), oblate (dashed line), and prolate (dot-dashed line) spheroids at zero inclination and with outer scattering radii along the z -axis of 0.3 and $1.2 \times$ the radius in the x - y plane, respectively; disk with an aspect ratio of 0.2 , inclinations of 0° (dotted line) and 60° (triple-dot-dashed line). Other parameters are as described in the main text. The horizontal dotted line represents a quasar to host ratio with an extended flux equal to half the average of the Kukula et al. (2001) galaxies.

number density to produce an optical depth to scattering of 0.05 increases the ratio to 11.2 . For the disk-like scattering region at an inclination of 90° and a uniform electron number density of 10^7 m^{-3} , the quasar to extended-flux ratio varies from 5.0 (aspect ratio of 0.05), through 2.6 (aspect ratio of 0.1) to 1.5 for an aspect ratio of 0.2 . The average quasar to “host” ratio for the quasars at $z = 2$ listed in Kukula et al. (2001) is 3.6 . In Figure 2, we present the quasar/extended-emission flux ratio as a function of optical depth for various spheroid and disk models with $\alpha = 0$, showing when the extended-emission levels become comparable to those observed by Kukula et al. (2001). With an optical depth of only 0.1 , scattering can easily produce $\gtrsim 50\%$ of the detected extended flux. Such small optical depths and the implied absorption depths are consistent with the average extinction suffered by quasars (e.g., Hopkins et al. 2004).

4. DISCUSSION

A quasar point source embedded in a geometry similar to either disk or spheroid galaxy types can produce significant extended flux. The question remains is this likely to make a significant contribution to the actual observed extended flux? Kukula et al. (2001) illustrated their observations in similar encircled energy versus radius plots and our Figure 1 can be compared to their Figure 4. It is readily apparent that scattering in a spherical distribution of scattering elements can produce very similar results to the observations reported by these authors. Indeed, the models presented in our Figure 1 exceed the extended-flux levels reported.

If the scattering particles are free electrons, rather than dust grains as in the models shown in Figure 1, the number densities required to produce extended-flux levels comparable to those observed are of the order of 10^6 – 10^7 m^{-3} . This is a similar order of magnitude to the average warm interstellar medium (ISM) in our Galaxy at 10^6 m^{-3} (Ferrière 2001, and references therein). A quasar is likely to ionize the tenuous component of the ISM to a distance of several kpc (Netzer et al. 2004) and models of

$z = 6$ galaxies (Yu & Lu 2005) suggest that quasar host galaxies could be nearly totally ionized. The uniform dust number density in the models illustrated in Figure 1 is of the order of that expected for a normal galaxy based on the ρ_d/ρ_H ratios for our Galaxy (Congui et al. 2005). Host galaxies of quasars are in general bluer than inactive galaxies (Canalizo et al. 2006, 2007; Jahnke et al. 2007), a fact that is used to infer a high rate of star formation, but could be explained by the wavelength dependence of dust scattering. Dependent on the medium, constraints to the magnitude of the scattered component may prove observable. As examples, in the case of electron scattering the presence and strength of recombination lines is observed;⁴ for dust scattering the color of the resultant extended emission can be observed. Such detail will be the subject of a forthcoming modeling paper.

In the local universe, the ratio of quasar to host galaxy luminosity can be as large as 2 orders of magnitude. For example, for a selection of quasars with an average redshift of $z = 0.17$ this ratio is ~ 25 (Wolf & Sheinis 2008). However, studies of $0.4 \lesssim z \lesssim 3$ quasars (Kukula et al. 2001; Floyd et al. 2004; Falomo et al. 2008) frequently find ratios between 1 and 10, sometimes less than 1. Given that quasars were significantly more luminous at earlier epochs, this would seem to require strong evolution of the host galaxy, if scattering of nuclear light is insignificant. In fact, the inferred decrease in host luminosity from $z \sim 1$ to $z = 0$ is significantly smaller than the decrease in quasar luminosity (Kukula et al. 2001). However, if scattering dominates the extended emission, as seems to be the case in at least some type 2 quasars (Zakamska et al. 2006), then relatively small decreases in the scattering optical depth can produce large increases in the quasar/host luminosity ratio. For example, it can be seen from Figure 2 that the scattered light quasar/“host” ratio is ~ 2 , for optical depths ~ 0.1 – 0.3 , but increases rapidly for optical depths < 0.1 . We suggest, therefore, that the apparent evolution of the quasar/host luminosity ratio arises because host galaxies at $z \sim 0$ contain less scattering material than their high-redshift counterparts. This might arise as a result of star formation, or because the less luminous quasar nucleus photoionizes a smaller fraction of the ISM. As the observed extended flux is a combination of scattered quasar and stellar emission, stellar features would still be present in the “host” spectra, albeit diluted by scattered light. Given the evolution of the quasar luminosity function with redshift, it is expected that these features would become more prominent in more recent epochs. The equivalent width of the stellar features may therefore provide a useful constraint on the strength of the scattered component.

RLQs are, on average, more luminous than their RLQ counterparts, by approximately 1 mag at $z = 2$ (Kukula et al. 2001). These authors also find that, on average, the hosts of radio-loud objects are the more luminous by 1.5 mag at the same epoch. If scattering contributes significantly to the observed extended emission then, as already stated, the perceived luminosity of the host will be loosely tied to that of the quasar. In this case, the finding of brighter radio-loud hosts is possibly a natural consequence of the average intrinsic luminosity difference between RLQs and RQQs.

In the local universe, radio-loud objects are predominantly associated with elliptical galaxies and radio-quiet objects with disk galaxies. Studies of host galaxies at high redshift have concluded that quasars generally inhabit elliptical galaxies

⁴ Only the case with uniform number density of 10^7 m^{-3} and an outer radius of 20 kpc will produce a significant line luminosity.

regardless of radio power (e.g., Kukula et al. 2001). However, if scattering is of importance, it is possible that the observed radial profiles may be influenced as much by the electron or dust distribution as the stellar light distribution, raising doubt as to the actual galaxy type. This possibility will be explored in greater depth in a forthcoming paper.

Scattering in the host galaxy around quasars, whilst providing extended flux, is merely a reflection of the quasar itself. Thus, any changes in the luminosity of the AGN will propagate out as a moving light echo. Bennert et al. (2008) present observations of several relatively low-redshift ($z = 0.14\text{--}0.21$) quasars that show shells and other structures that these authors attribute to merger remnants. Whilst we have no direct polarimetry evidence to refute that assertion, we speculate that some of the structures observed in these objects might actually be light echoes resulting from past high-luminosity outbursts from the quasar.

It has been concluded (Kukula et al. 2001; Floyd et al. 2004; Falomo et al. 2008) that the host galaxies of quasars are essentially fully formed by $z = 2$, or earlier, and then undergo passive evolution to the current epoch. Other authors (Falomo et al. 2008; Schramm et al. 2008) determined that the host galaxies of the quasars were a factor of 3 to 5 times more luminous than allowed by passive evolution alone. However, scattering in the host galaxy can easily contribute a significant fraction of the extended flux detected around quasars at high- z , leading to overestimates of the host luminosities and masses, which in turn may give rise to a misleading picture of evolutionary trends.

5. SUMMARY AND CONCLUSIONS

We have presented models that indicate that scattering in the ISM of the host galaxy around quasars could significantly alter the characterization of the host themselves. Whilst scattering may be no more than a nuisance effect at low- z , with the increase in the quasar luminosity with increasing redshift this may represent a major problem for host galaxy studies. Indeed, it is possible that the stellar emission from the actual host has not been detected for high-redshift quasars. For electron scattering, a number density of the same order as that in the Milky Way, together with a high ionization degree ($\sim 50\%$) is required. If the scattering medium is predominantly dust grains and uniformly distributed, then a dust number density similar to that in our Galaxy can produce the required extended flux without the requirement for a high degree of ionization.

Such scattering naturally explains the trend for more luminous “hosts” around the brighter RLQs compared to those of the RQQs, since the extended flux is directly related to the luminosity of the quasar. If the real host has not been detected, or at least overestimated in terms of its luminosity, then it is not possible to determine evolutionary trends with any degree of accuracy. One obvious observational test of the idea presented in this Letter is to repeat the high spatial resolution observations of high-redshift quasars made by other authors but include a polarimetry module to determine the polarization parameters of

the potential scattered flux. High spatial resolution is essential to this type of observation to avoid smearing out the polarization and rendering it undetectable.

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